

HEAT FLUX, MASS LOSS RATE AND UPWARD FLAME SPREAD FOR BURNING VERTICAL WALLS

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NIST

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**Annual Report May 1990
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Notice

This report was prepared for the Center for Fire Research of the National Institute of Standards and Technology under Grant Number 60NANB8D0849. The statements and conclusions contained in this report are those of the authors and do not necessarily reflect the views of the National Institute of Standards and Technology or the Center for Fire Research.

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by

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Submitted to Center for Fire Research
National Institute of Standards and Technology
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ABSTRACT

Progress made during the first year of NIST Grant No. 60NANB8D0849 for the period ending August 14, 1989 is reported here. The overall objective of the grant is to understand the basic mechanisms of upward flame spread and to develop a methodology to predict the flame spread on practical wall materials, appropriately verified by experiments. In this report, progress made on the following tasks is described in individual sections, upward flame spread experiments, mathematical model, local mass loss rate apparatus, heat conduction in the interior of burning walls, and Gardon heat flux gage calibration.

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ANNUAL PROGRESS REPORT

for the period August 15, 1988 to August 14, 1989

on NIST Grant No. 60NANB8D0849

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A. K. Kulkarni, Principal Investigator

C. I. Kim, Graduate Research Assistant

C. H. Kuo, Graduate Student

INTRODUCTION

This annual report describes progress made during the period August 15, 1988 through August 14, 1989 on the project, Upward Flame Spread on a Vertical Wall, supported under grant no. 60NANB8D0849. It is the first year of the grant, although some experimental and theoretical work on upward flame spread was also done in the previous year (ending August 14, 1988) at NIST while Dr. Kulkarni was on a sabbatical leave and it was reported in the last annual report, issued as NIST-GCR-89-565.

The overall objective of the current project is to understand the basic mechanisms of upward flame spread and to develop a methodology to predict the flame spread on practical wall materials, appropriately verified by experiments. Specifically, the study involves (i) design and fabrication of an experimental setup to study upward flame spread, (ii) measurement of heat feedback from flames to the yet-unburnt surface ahead of the pyrolysis front (or simply, the forward heat flux), (iii) correlation of the heat flux data for further modeling purposes, (iv) measurement of upward flame spread rate of the flame tip and the pyrolysis front, (v) development of a suitable mathematical model to predict upward flame spread, (vi) identification, and if necessary, measurement,

of "fire properties" of practical materials for use in the model, and (vii) comparison of data with predictions and model revisions.

The above objectives were envisioned to be met in an approximately two-year project, for which this report presents progress made in the first year. Major milestones achieved this period are

- (i) an experimental setup was designed and setup for measurement of the forward heat transfer and upward flame spread rate, and some test runs were made,
- (ii) local mass loss rate apparatus was designed and set up,
- (iii) a numerical model was developed to predict the flame spread and some results were obtained,
- (iv) experimental data sets for some materials were obtained and compared with the model.

In addition to the above, the following related tasks were undertaken:

- (v) transient heat conduction in the interior of a burning wall was measured and analyzed as a function of height for two materials,
- (vi) a calibration setup was designed and fabricated for circular foil (Gardon) heat flux gages.

Sections A through E that follow contain details on the tasks accomplished.

Activities on publications and theses during the last year related to the NIST grant are given below.

Publications

- Kulkarni, A. K. and J. J. Hwang. Experiments on Vertical Wall Fire in a Stratified Ambient Atmosphere. Poster paper presented at the Twenty-second International Symposium on Combustion, included in the book of Abstracts, The Combustion Institute, Pittsburgh, PA. 1988.
- Kulkarni, A. K. and S. L. Chou. Turbulent Natural Convection Flow on a Heated Vertical Wall Immersed in a Stratified Atmosphere. Journal of Heat Transfer, Vol. 111, pp. 378-384, 1989.
- Hwang, J. J. and A. K. Kulkarni. An Experimental Study of Vertical Wall Fire in a Stratified Ambient Atmosphere. Experimental Thermal and Fluid Science (an International Journal), Vol. 2(2), pp. 216-223, 1989.
- Kulkarni, A. K. and S. Fischer. A Model for Upward Flame Spread on Vertical Wall. Proceedings of the 1988 Technical Meeting of the Eastern Section of the Combustion Institute, pp. 72-1 - 72-4, 1988.
- Kulkarni, A. K. Suppression of Fires and Flammability of Spacecraft Materials in Microgravity. Published in the proceedings of the International Microgravity Combustion Workshop, NASA-Lewis, January 1989.
- Kulkarni, A. K. and C. I. Kim. Heat Loss to the Interior of a Free Burning Vertical PMMA Slab and Its Influence on Heat of Pyrolysis, proceedings of the 16th National Heat Transfer Conference, Heat Transfer Phenomena in Radiation, Combustion and Fires, HTD, Vol. 106, pp. 359-365, 1989.
- Kulkarni, A. K. and S. Fischer. Upward Flame Spread on Vertical Walls: Model and Experiments. Accepted for presentation at the III International Seminar on Fires, Alma-Ata, USSR, (included in the Book of Abstracts, paper no. 4.5), 1989.
- Kim, C. I. and A. K. Kulkarni. A Numerical Model for Upward Flame Spread, Submitted to the 1989 Fall Technical Meeting of the Combustion Institute.

Theses

Kim, C. I., Upward Flame Spread on Vertical Walls, Ph.D. Thesis in progress.

C. H. Kuo, Analysis and Calibration of Circular Foil Heat Flux Gages, M.S. Thesis
in progress.

Section A: UPWARD FLAME SPREAD EXPERIMENTS

An experimental setup, somewhat similar to the one constructed at NIST in the previous year, but on a smaller scale, was designed and constructed as shown in Figure A1. A metal frame holds flat samples of 30 cm width and 1.2 m height in a vertical position. Around the sample (above and to the sides) are inert wall panels of marinite flush with the sample front surface. A T-shaped linear natural gas burner pilot was made which provides approximately flat vertical flame of desired, adjustable height (normally 10 cm to 25 cm) to ignite wall samples. The 30 cm width of the samples is expected to ensure predominantly two-dimensional boundary layer-type flames near the center region of the wall. The inert walls on the side prevent any air drafts from behind the sample and the top inert panel ensures continuation of wall flame having air entrainment from only the front side, simulating a real wall fire.

The major instrumentation includes Gardon type, 0.5 inch diameter, total heat flux gages embedded in the sample along the vertical center line, and video and still photography with flood lighting. The gages, which are shown in a photograph in Figure A2, are small in size to allow an acceptable space resolution, but sufficiently sensitive and accurate for desired measurements. The gages are mounted at intervals that increase exponentially with the height. Thermocouples to measure surface temperatures of the sample during the upward spread are planned to be added if necessary. The power output of the pilot burner is determined using a flow meter in the natural gas supply line. An automatic data acquisition system has been installed and programmed to take necessary measurements. The experimental setup is complete and some test runs have been made as discussed later. In initial test runs, the samples burned well, however, as the tests progressed, several events/observations/problems were noted, which required modifications to the apparatus. Some of them were

(i) water condensation on the heat flux gages (to overcome this difficulty a separate water heater was installed to supply hot water to the gages as the heat sink), (ii) a better design for the line burner used for ignition (the joint at "Tee" melted!), (iii) a need for a better bond between the sample and the substrate, (iv) smoke leak on the rear side of the sample, (v) a need for modification in the data acquisition program, etc. The test apparatus was suitably modified to take care of the problems encountered in the initial trial runs.

The first set of experiments was conducted using cardboard samples in the upward flame spread test apparatus. The measured heat flux data as a function of time at various locations are presented in Figure A3. Also shown in this figure are fifth order polynomials used to fit the data. Figure A4 shows the measured flame height (x_f) and pyrolysis height (x_p) data for cardboard. The typical fluctuations in x_f are shown by "+" symbols and the average is indicated by a solid circle. The uncertainty in x_p is approximately ± 5 cm. The heat flux data for cardboard are replotted in Figure A5 with normalized height x/x_f . The experiments are in progress using various materials and the data are being reduced mainly (i) to deduce a forward heat flux correlation for input into a mathematical model and (ii) to measure x_f and x_p , so that these values are available for comparison with the results of the model.

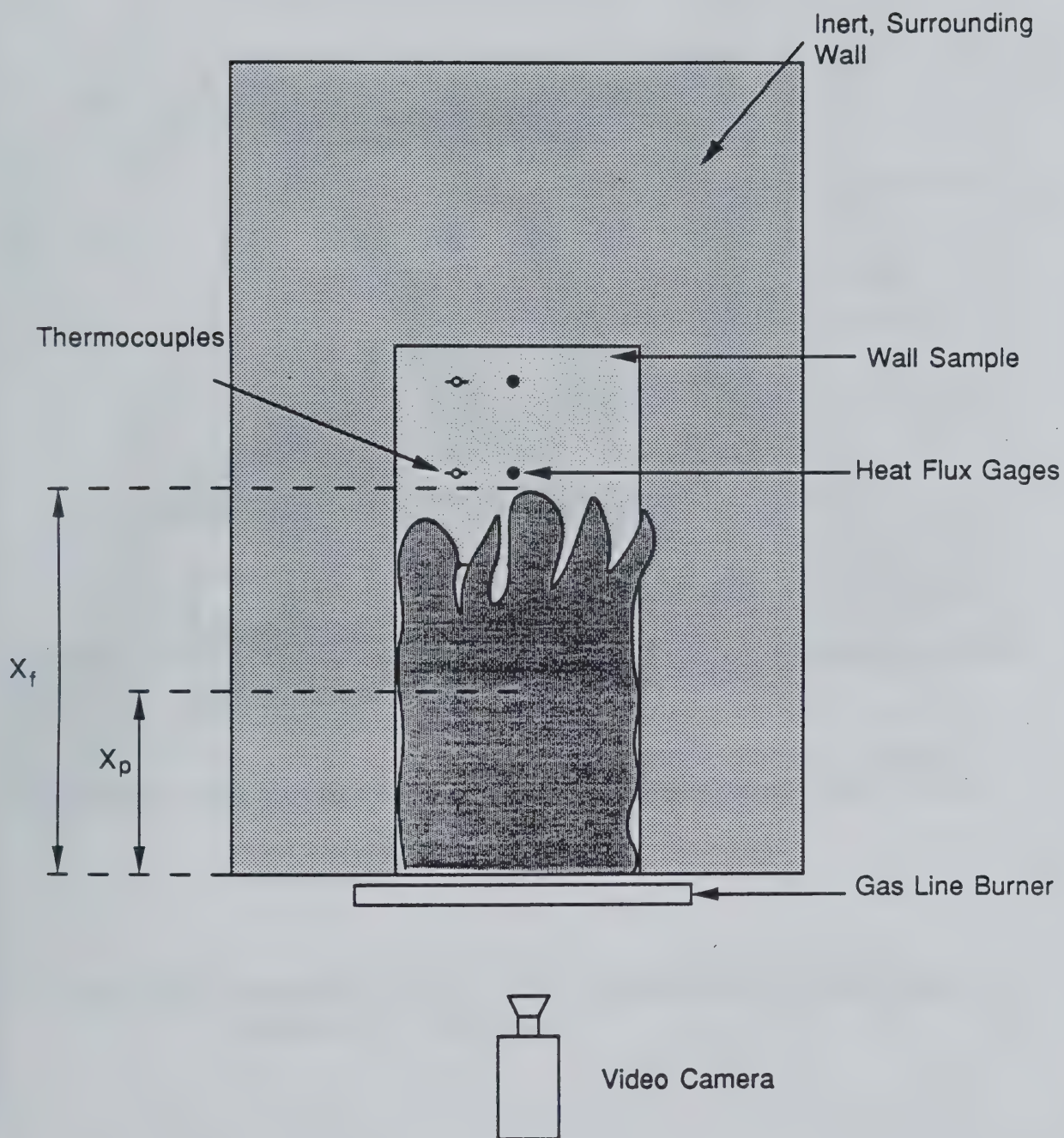
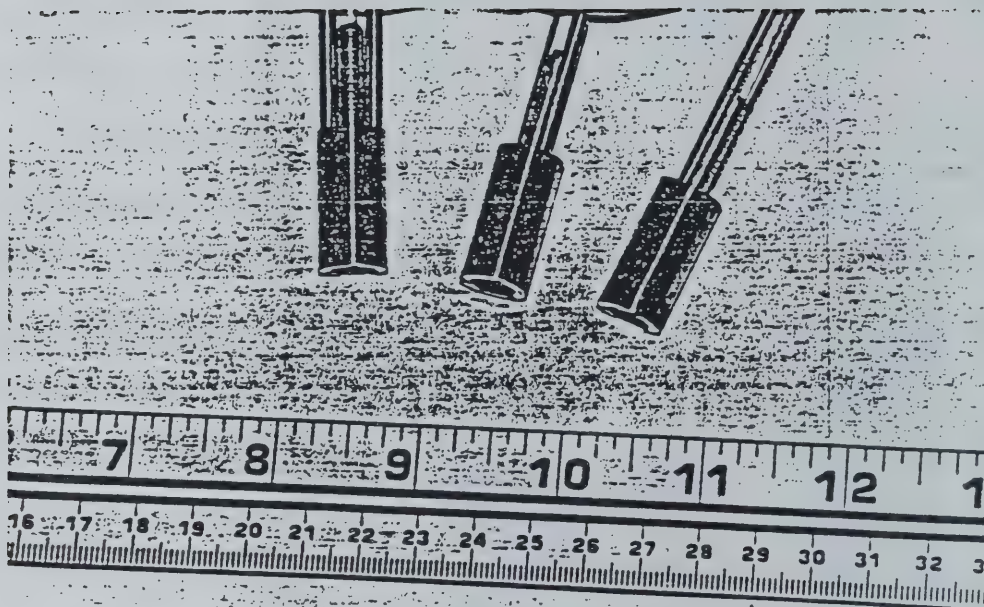
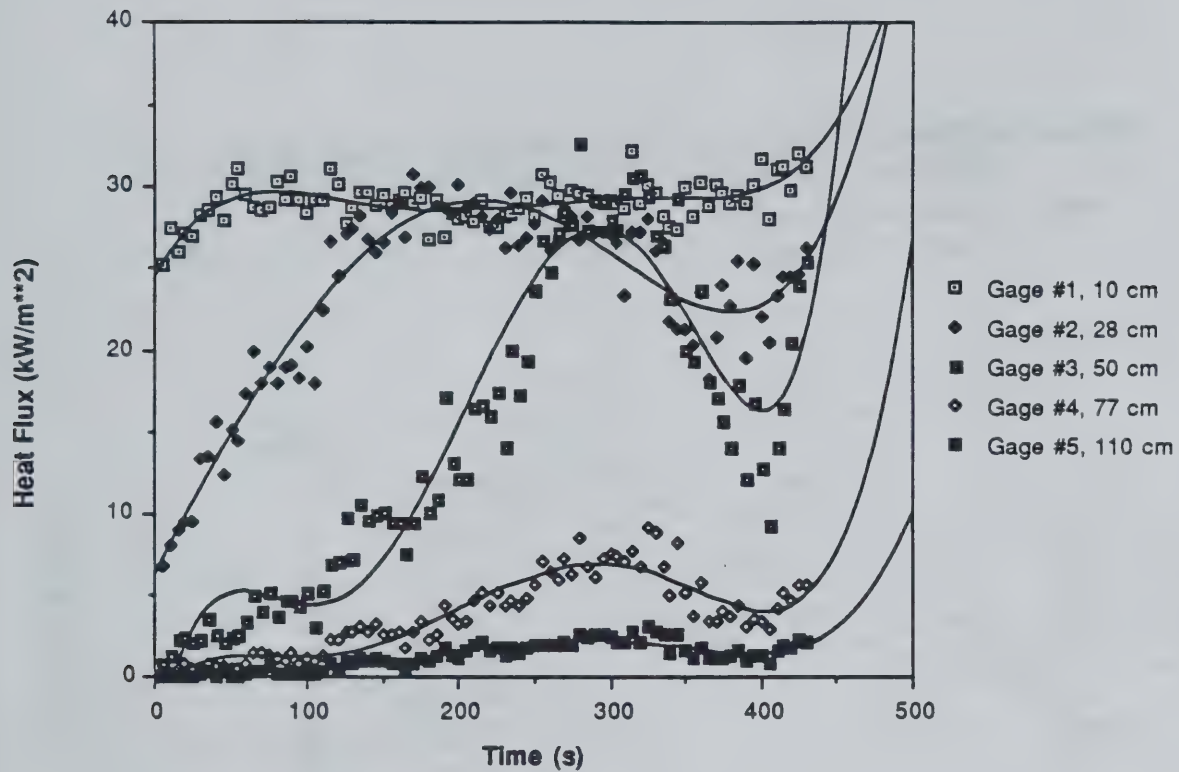


Figure A1. A Schematic of the Apparatus for Upward Flame Spread Studies.



FigureA2 : Gardon type total heat flux gages used in the above apparatus.

Heat Flux Measurement for Card Board



$$\begin{aligned}
 y_1 &= 24.504 + 0.18178x - 2.2145e-3x^2 + 1.1419e-5x^3 - 2.6387e-8x^4 + 2.2633e-11x^5 \quad R^2 = 0.459 \\
 y_2 &= 6.3218 + 0.17872x - 8.3734e-5x^2 - 1.2792e-6x^3 - 6.8222e-10x^4 + 5.6378e-12x^5 \quad R^2 = 0.910 \\
 y_3 &= -4.8864 + 0.49472x - 8.3630e-3x^2 + 5.7838e-5x^3 - 1.5906e-7x^4 + 1.4958e-10x^5 \quad R^2 = 0.910 \\
 y_4 &= -1.2729 + 0.11910x - 1.9382e-3x^2 + 1.3381e-5x^3 - 3.6908e-8x^4 + 3.4790e-11x^5 \quad R^2 = 0.859 \\
 y_5 &= -0.35988 + 2.9957e-2x - 4.9882e-4x^2 + 3.7096e-6x^3 - 1.0790e-8x^4 + 1.0588e-11x^5 \quad R^2 = 0.841
 \end{aligned}$$

Figure A3. Measured Heat Flux as a Function of Time at Various Locations for Cardboard.

Measured Flame Height and Pyrolysis Height for Card Board

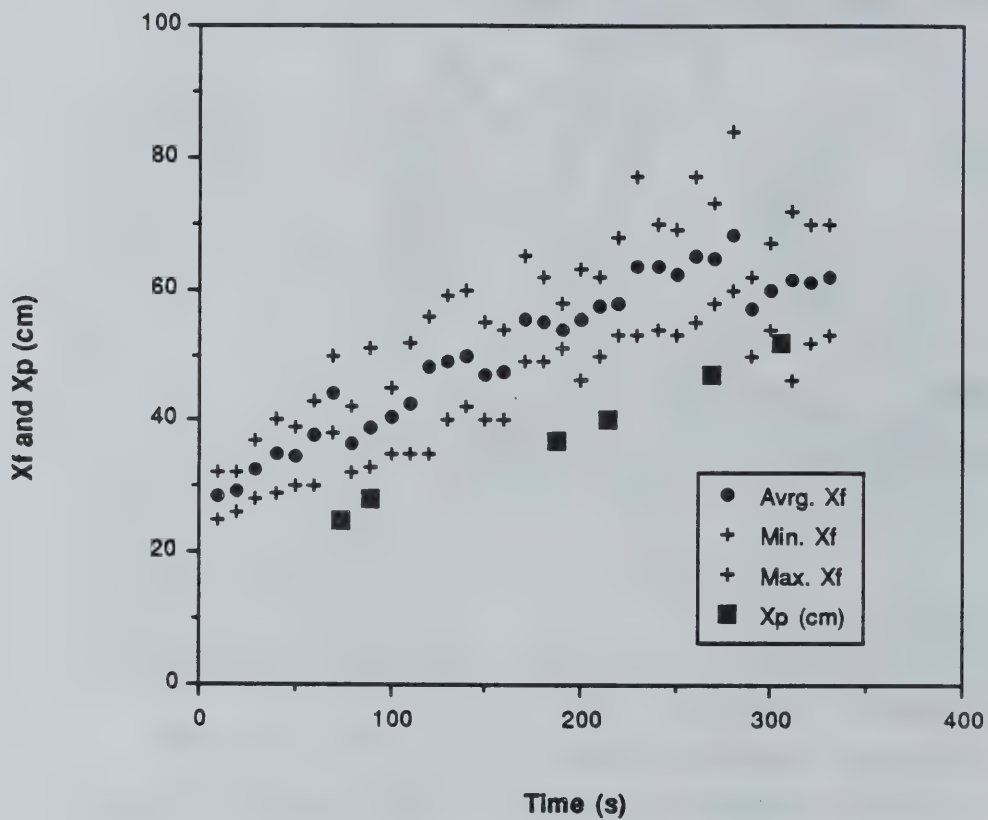


Figure A4. Measured Flame Height and Pyrolysis Height for Cardboard.

Heat Flux Data with Normalized Height for Cardboard

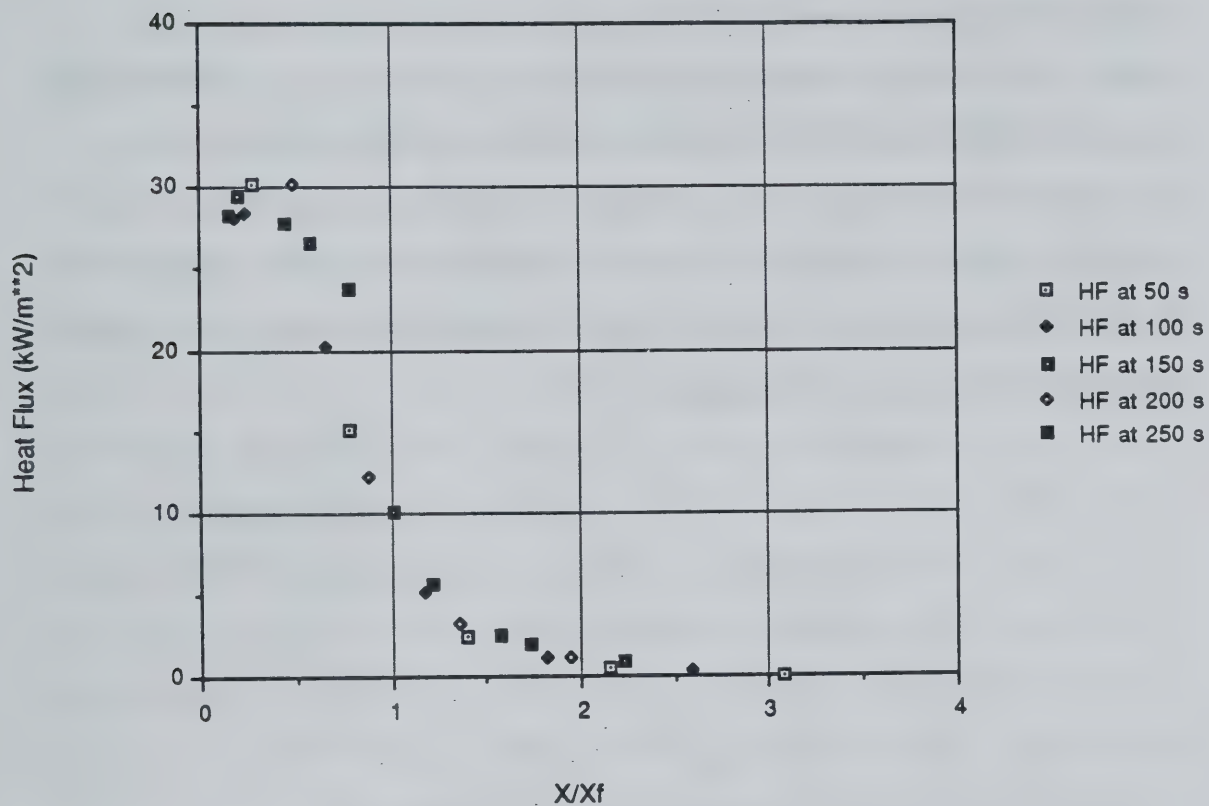


Figure A5. Measured Heat Flux vs. Normalized Height for Cardboard.

Section B: MATHEMATICAL MODEL

A numerically comprehensive mathematical model, taking into account more realistic distribution of the forward heat flux and initial temperature distribution was developed. In this model the forward heat flux is allowed to vary with the distance above the pyrolysis front (as opposed to being a constant between the pyrolysis front and the flame height, and zero above the flame height). The initial temperature of the solid is also allowed to vary with the height (which occurs because of the igniter hot plume during the preignition period). More details on this model, some calculations, and comparisons with data are included in a paper submitted to the 1989 Technical Meeting of The Eastern Section of the Combustion Institute which is attached below after making slight modifications as a part of this section.

A Numerical Model for Upward Flame Spread

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Introduction

Upward flame spread is the most rapid and hazardous of the different modes of fire spread on a vertical wall (upward, lateral, and downward) and, consequently, of great interest in the fire safety field. The rate of upward flame spread should be an important parameter in the ranking of the fire hazard offered by different materials. During the upward spread, flames from the pyrolyzing area continuously cover the unburnt fuel which is eventually ignited, and the size of the newly created flames in turn depends on the magnitude of the burning rate. Therefore, all models attempting to predict the upward spread rate must adequately account for the heat feedback from the flames to the nonpyrolyzing surface ahead of the pyrolyzing front, $\dot{q}_w''(x,t)$. A number of models proposed in literature so far differ mainly in how to model $\dot{q}_w''(x,t)$ appropriately. They generally depend on one or more simplifying assumptions such as the constant forward heat flux up to the flame height and zero thereafter, and a constant temperature (equal to the ambient temperature) of the wall surface above the flame tip height. In reality, the heat feedback from the flames to the unburnt wall surface decreases above the flame tip and for large upward spread fires, the wall may be heated to a significantly greater temperature compared to the ambient temperature by the hot plume gases even before the flame tip reaches there. However, no model has so far used the experimentally measured values of $\dot{q}_w''(x,t)$ as input to the model.

In the present model, previously measured heat feedback data [3] were curve-fitted, and an exponentially decaying form was assumed for wall temperature, $T_w(x,t)$ (Figure B1), and used as input to the upward flame spread model. The model also accepts additional "fire properties" of wall material as an input which are obtained from experimental data. Specifically, the time history of local mass burning rate $\dot{m}''(t)$, and the product of conductivity, density and heat capacity, $k\rho c$, for a specific wall material configuration are key properties that are incorporated into the model.

Theoretical Analysis

The process of upward flame spread is assumed to continue in the following manner: as the surface temperature reaches a certain characteristic temperature (T_{ig}) because of the flame heat feedback, the surface starts to pyrolyze significantly, and the pyrolysis front is assumed to have reached that location. Because the flame spread rate is directly related to the time history of the pyrolysis height, we need to trace the surface temperatures to get the pyrolysis height. Other assumptions are: the ignition temperature does not vary with location; there is no heat conduction in the solid in x-direction; the material is inert during the heating process.

The surface temperature of a semi-infinite slab (T_s), initially at the temperature of T_o subjected to the external flux of $\dot{q}''_w(x,t)$ is given by [1],

$$T_s(x,t) = T_o + \frac{1}{\sqrt{\pi k \rho c}} \int_0^t \frac{\dot{q}''_w(x,t')}{\sqrt{t-t'}} dt' \quad (1)$$

where $\dot{q}_w''(x,t)$ is obtained from curve-fitting experimental data and it can be written in the form,

$$\dot{q}_w''(x,t) = \dot{q}_{wo}'' g \{ x_b(t), x_p(t), x_f(t), x \} \quad (2)$$

where \dot{q}_{wo}'' is a "fire property" of the wall material and g is a generalized function of burnout edge (x_b), pyrolysis height (x_p), and flame tip height (x_f).

The flame tip height is obtained from an available correlation [2],

$$x_f(t) - x_b(t) = K \left[\dot{Q}'(t) + h_c \int_{x_b(t)}^{x_p(t)} \dot{m}'' dx \right]^n \quad (3)$$

where \dot{Q}' is the igniter strength (kW/m), h_c is the heat of combustion of the fuel, K and n are experimentally obtained constants, and \dot{m}'' and x_b are described as,

$$\begin{aligned} \dot{m}''(\lambda) &= a_4 \lambda^4 + a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0 ; \text{ if } \lambda < t_b \\ \dot{m}''(\lambda) &= 0 ; \text{ if } \lambda > t_b \end{aligned} \quad (4)$$

$$x_b(t) = x_p(t - t_b) \quad (5)$$

where λ is a local time which is the time after that local point reaches the ignition temperature. t_b is the burnout time which is the time period from the instant of ignition to the end of pyrolysis at a given location. $\dot{m}''(\lambda)$ is assumed to be a material "fire property" and independent of the location. $\dot{m}''(\lambda)$ for 1/2" thick particle board is shown in Figure B2 [4].

The above set of equations is solved with a numerical procedure that involves finite difference method and numerical integration. Figure B3 shows the pattern of the grid that represent the surface of the wall, and Figure B4 shows the flow chart of the numerical procedure.

Results

Depending upon the igniter strength, the height of the initially ignited portion of the sample, x_{po} , (which has a surface temperature of T_{ig}) is determined. The surface temperature above the initial pyrolysis height x_{po} is assumed to be exponentially decaying (Figure B1). The functional form of $\dot{q}_w''(x,t)$ is such that the forward heat flux is constant up to the flame tip height then exponentially decays. This is generally consistent with previous experimental results [3]. With these conditions, numerical computations are performed for various wall materials. Figure B5 shows flame tip height prediction for 1/2" thick particle board. When compared to the experimental results of Kulkarni [4], the computations overpredict the data. However, considering the fact that the estimation of x_f in the experiments was based on the highly visible and continuous flame tip, the actual x_f might have been higher and thus closer to the prediction. Figure B6 shows the pyrolysis height prediction for particle board and masonite. Experimental results for these two materials in this time domain were not available for comparison, but x_p measured at $t \cong 300$ s for masonite was 110 cm which is close to the prediction.

Conclusion

An upward flame spread model is presented here in which the improvement over previous models is that the distribution of forward heat flux is

taken directly from experimental data, and a more realistic initial surface temperature is used. Preliminary results show that the flame tip height and pyrolysis height are predicted with reasonable accuracy.

Support for this work was provided by Center for Fire Research, National Institute of Standards and Technology under Grant No. 60NANB4D0037.

References

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- [2] Delichatios, M. A. "Flame Heights in Turbulent Wall Fires with Significant Flame Radiation," Comb. Sci. and Tech. 34, p195, 1984.
- [3] Quintiere, J. and Harkleroad, M. "Wall Flames and Implications for Upward Flame Spread," Comb. Sci. and Tech. 48, p191, 1986.
- [4] Kulkarni, A. K. "Upward Flame Spread on Vertical Walls," Final Report on Grant No. 60NANB4D0037 submitted to Center for Fire Research, National Institute of Standards and Technology, 1989.

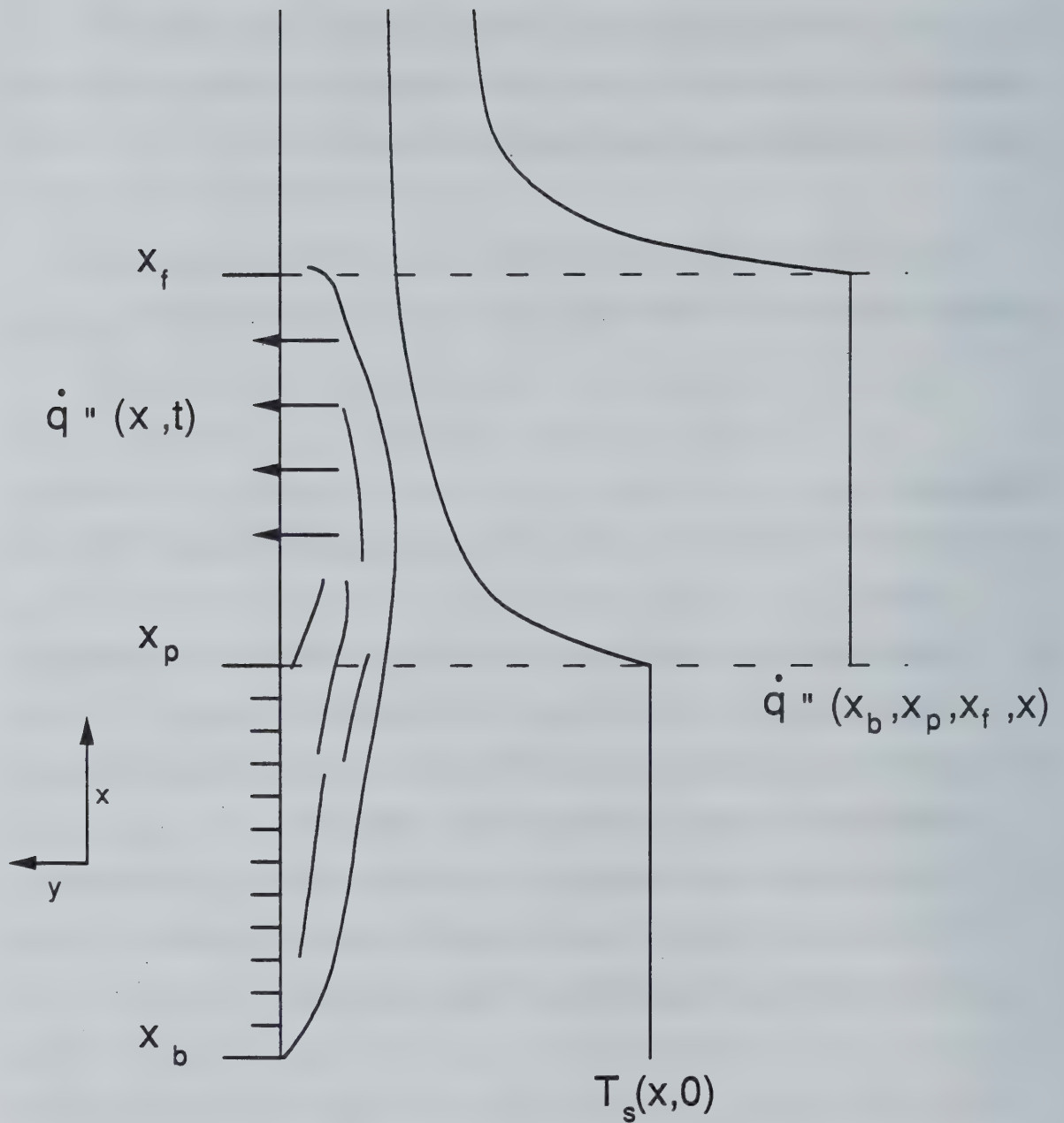


Figure B1. Schematic of Upward Spreading Wall Fire and Forward Heat Flux and Initial Surface Temperature.

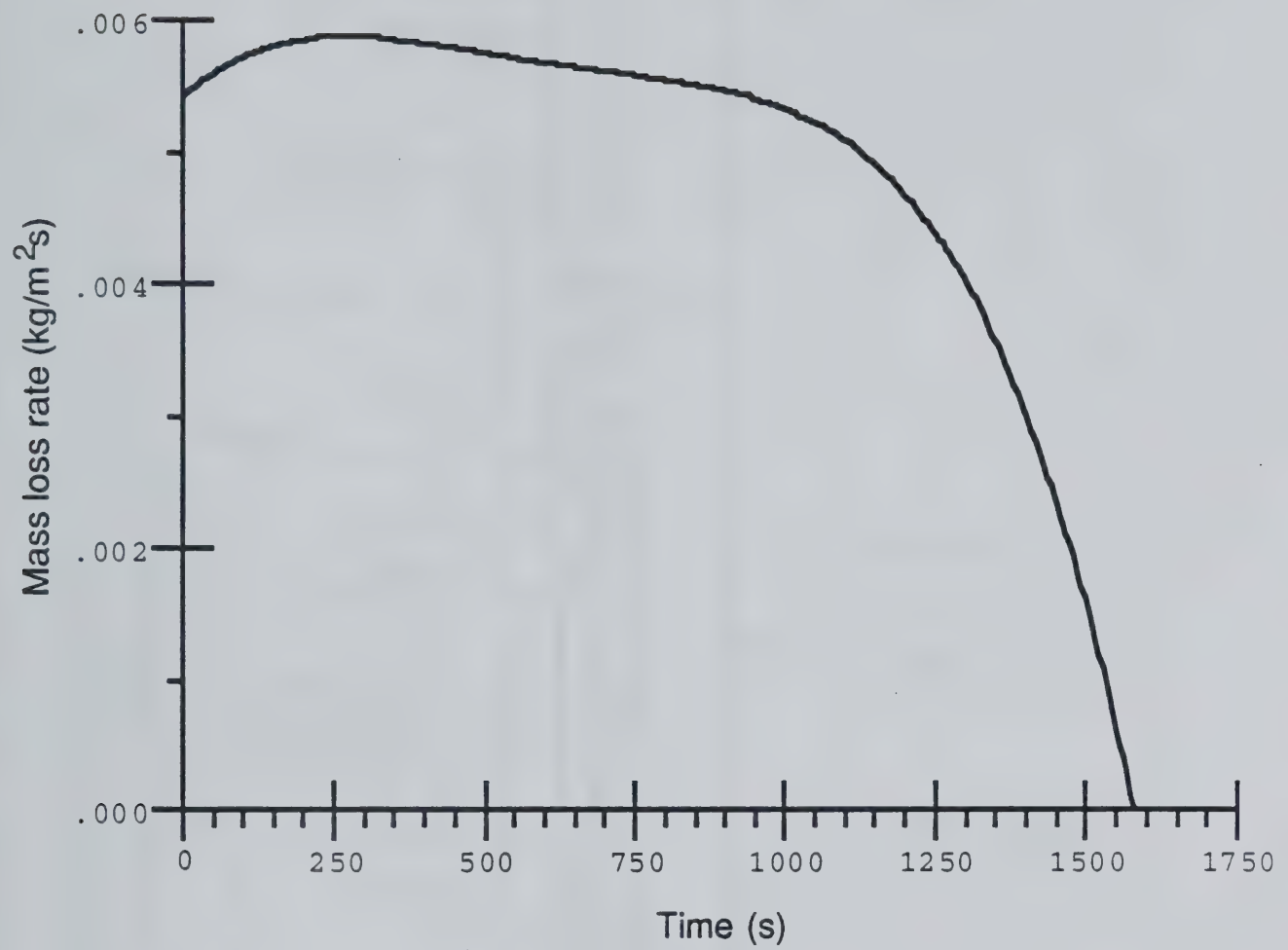
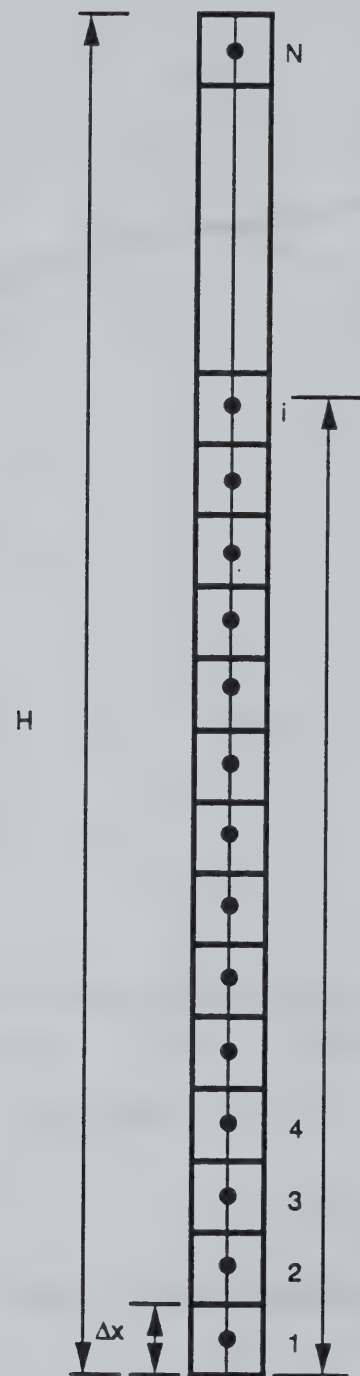


Figure B2. Mass Loss Rate vs. Time for 1/2" Thick Particle Board



$$X_i = \Delta x/2 + \Delta x(i-1) = \Delta x(i-0.5)$$

$$\Delta x = H/N$$

Figure B3. Grid Pattern for Upward Flame Spread Model.

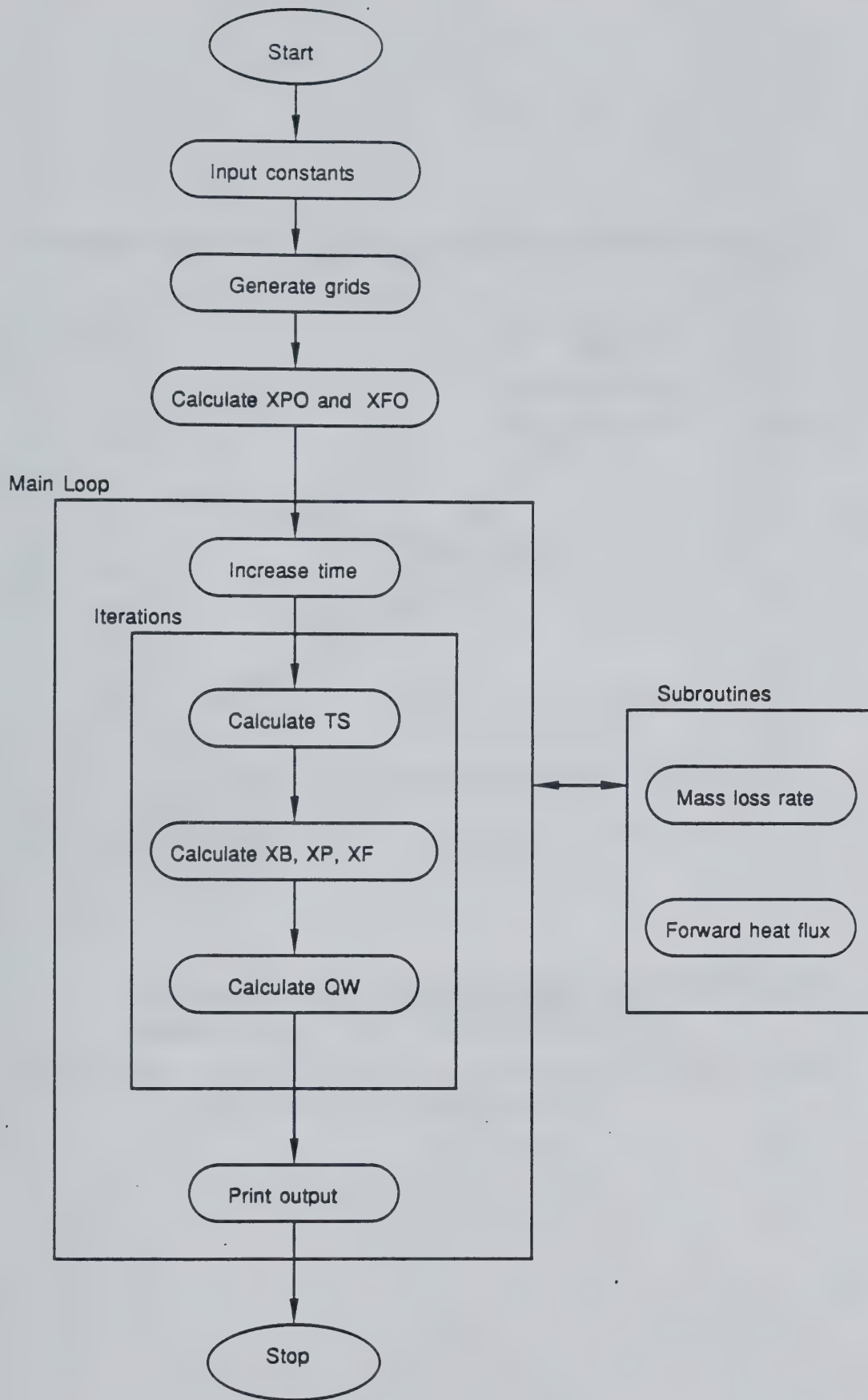


Figure B4. Flow Chart for Upward Flame Spread Model.

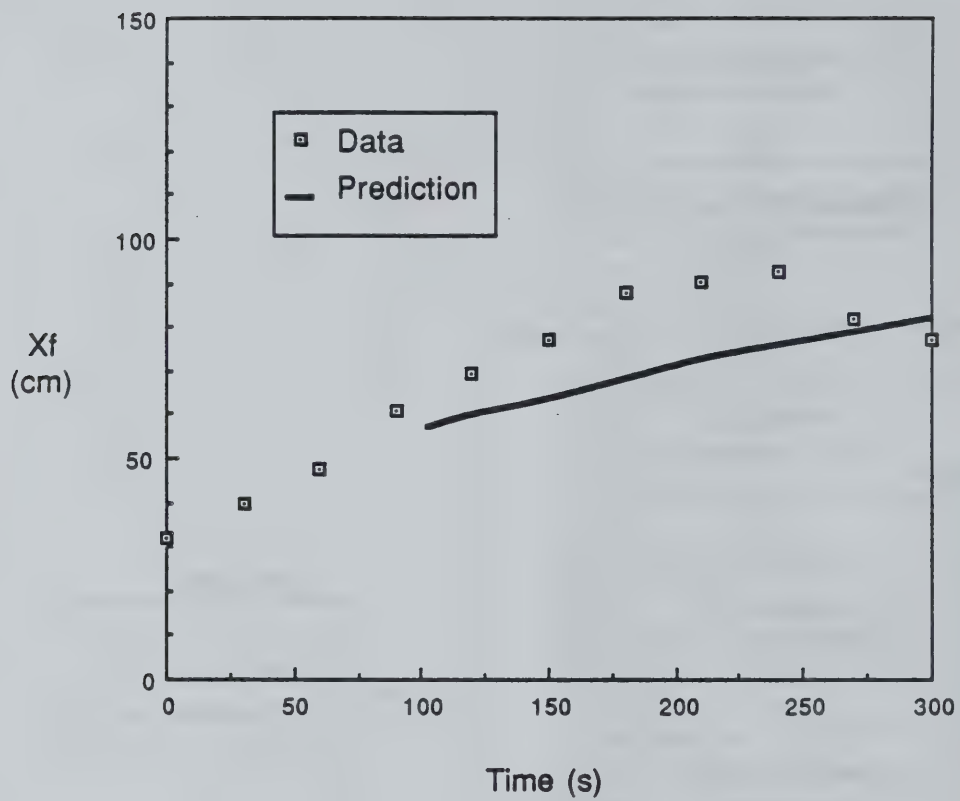


Figure B5. Flame Height Prediction and Comparison with Data [4] for 1/2" Thick Particle Board

Predicted Pyrolysis Height for Particle Board and Masonite

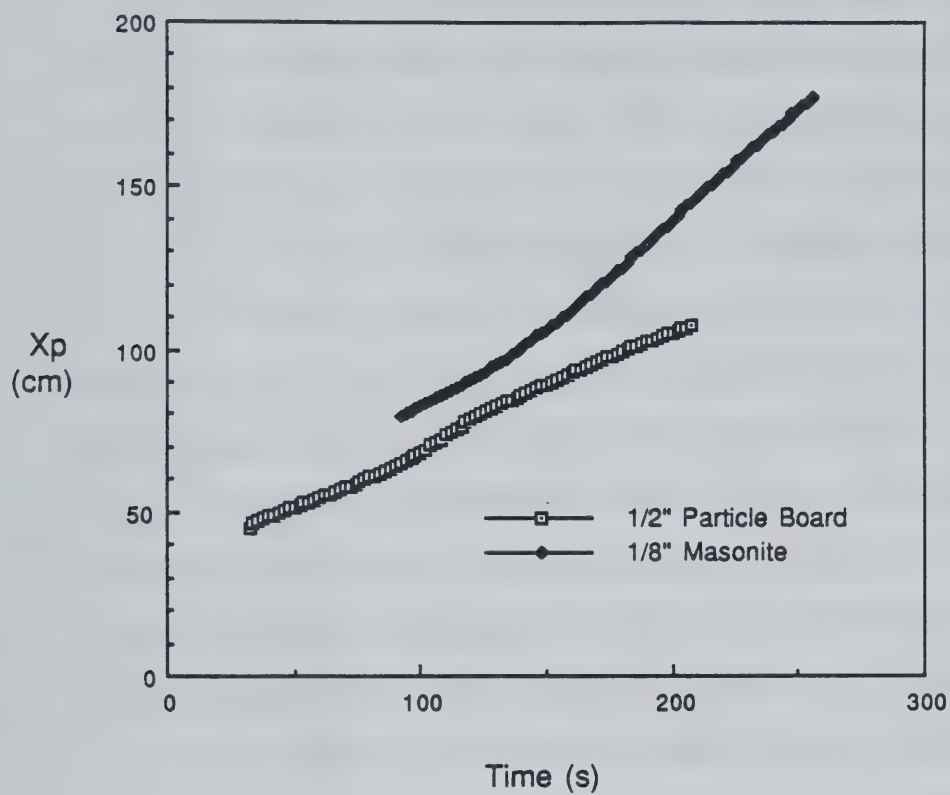


Figure B6. Pyrolysis Height Predictions for 1/2" Thick Particle Board and 1/8" Thick Masonite.

Section C: LOCAL MASS LOSS RATE APPARATUS

All models attempting to predict upward spread rate must adequately account for the mass loss rate of the pyrolyzing material. Therefore, an experimental setup was designed to simulate the local mass loss rate in an upward spreading vertical fire situation. Again, the design for this apparatus was based on our past experience at NIST where a similar apparatus was setup. This is accomplished by attaching 12cm × 12cm thin wall material to thick substrate and placing it adjacent to turbulent flames from a natural gas line-burner (Figure C1). The experimental apparatus (Figure C2) includes an electronic balance with digital display and analog output port, a structure made of aluminum beams, a mounting plate for the sample, a surrounding wall that covers the mounting plate, and a counter weight. The time history of the mass of the sample is recorded through data acquisition system. The results are corrected for factors such as moisture loss and distortion of the aluminum beam, and curve-fitted to a polynomial. The experimentally obtained local mass loss rate will be used in our upward flame spread model. The apparatus is mostly setup and ready for taking data.

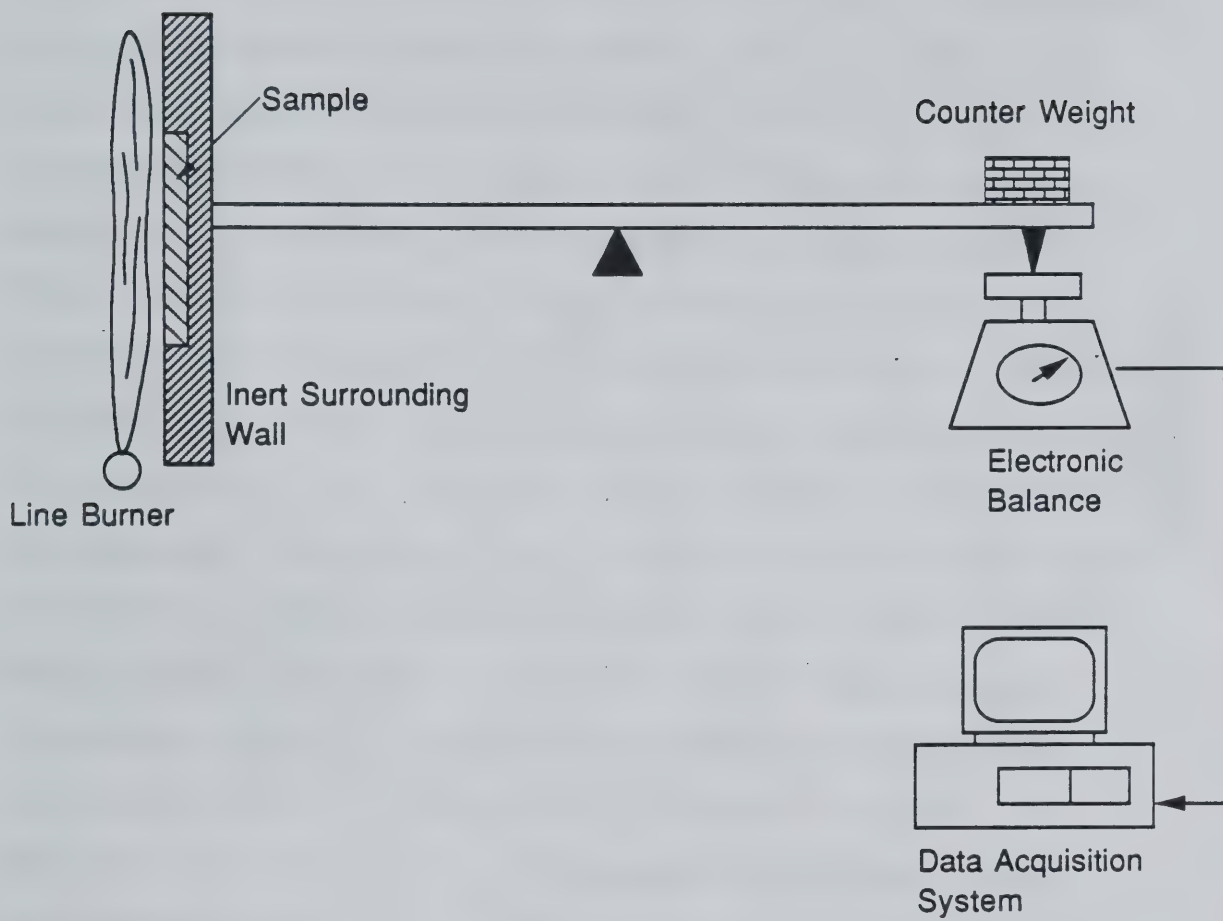


Figure C1. A Schematic of the Apparatus for Local Mass Loss Rate Measurements.

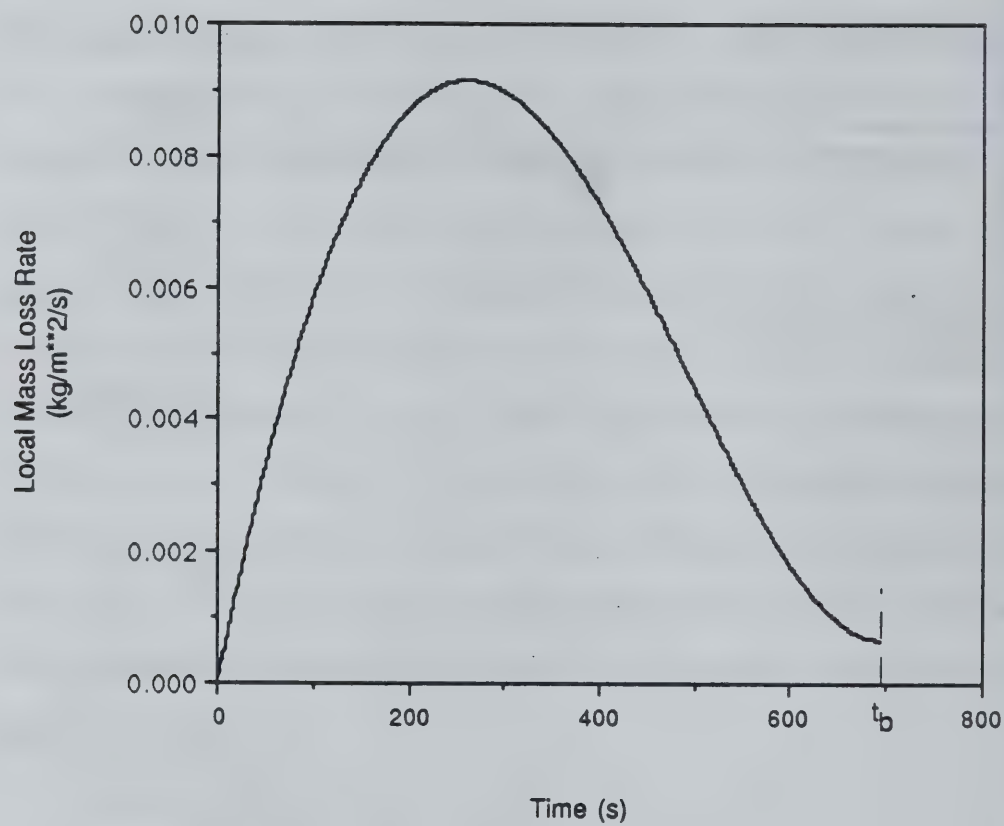


Figure C2. Local Mass Loss Rate for 1/8" Thick Black PMMA.

Section D: HEAT CONDUCTION IN THE INTERIOR OF BURNING WALLS

In the models involving wall fires (including the upward flame spread), one of the important properties of materials needed is an effective heat of gasification (h_g). Values reported for h_g for various materials in the literature often include the solid interior heat loss due to conduction and it is normally assumed that this value is a constant, although in reality, the interior heat conduction loss may decrease significantly with time. In order to verify this hypothesis, experiments were conducted in which conduction heat transfer into a vertical free burning PMMA (polymethylmethacrylate) slab was measured as a function of time and distance from the leading edge for clear and black PMMA, and its contribution to the known values of heat of gasification was estimated. The heat conduction into the pyrolyzing surface was deduced from measured temperatures in the interior of burning slabs. The surface conduction heat flux decreased from 14 kW/m² for clear PMMA and 13 kW/m² for black PMMA at $t=300$ s to almost 8 kW/m² at around $t=1000$ s and then reached a plateau, indicating a substantial degree of unsteadiness in the early part of combustion of slabs. It was concluded that, when estimating burning rates in numerical calculations one has to be careful in selecting a value for the heat of pyrolysis because of the generally unsteady nature of heat conduction into the solid interior. A full-length paper based on this work was prepared and presented at the 26th National Heat Transfer Conference. A revised version of this paper is attached below.

HEAT LOSS TO THE INTERIOR OF A FREE BURNING
VERTICAL WALL AND ITS INFLUENCE
ON ESTIMATION OF EFFECTIVE HEAT OF GASIFICATION

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ABSTRACT

Conduction heat transfer into a vertical free burning slab was measured as a function of time and distance from the leading edge, and its contribution to the known values of effective heat of gasification was analyzed. The present set of experiments were performed using clear and black PMMA (polymethylmethacrylate) samples. The heat conduction into the pyrolyzing surface was deduced from temperature measurements in the interior of burning slabs. The surface conduction heat flux decreased from 14 kW/m² for clear PMMA and 13 kW/m² for black PMMA at $t=300$ s to almost 8 kW/m² at around $t=1000$ s and then reached a plateau, indicating a substantial degree of unsteadiness in the early part of combustion of slabs. It is concluded that, when estimating burning rates in numerical calculations one has to be careful in selecting a value for the effective heat of gasification because of the generally unsteady nature of heat conduction into the solid interior.

NOMENCLATURE

A, B = constants in Eq. (3) and (4)

c_p = heat capacity, kJ/kg·K

h_g = effective heat of gasification, kJ/kg

h_p = heat of pyrolysis, kJ/kg

k = thermal conductivity, kJ/m·s·K

\dot{m}'' = burning rate per unit area, kg/m²s

\dot{q}_c'' = heat conduction to the interior at the pyrolyzing surface, kW/m²

\dot{q}_{CONV}'' = convective heat feedback from gas phase to the pyrolyzing surface,
kW/m²

\dot{q}_{EX}'' = radiative heat feedback from surroundings other than the flame absorbed
by the pyrolyzing surface, kW/m²

\dot{q}_{NET}'' = net heat flux causing the solid fuel to gasify, pyrolyze, and eventually
burn or be swept away with the surrounding gases, kW/m²

$\dot{q}_{\text{RAD FL}}''$ = radiative heat feedback from flames absorbed by the pyrolyzing
surface, kW/m²

\dot{q}_{RERAD}'' = radiation loss by the pyrolyzing surface to atmosphere, kW/m²

T = temperature, K

T_w = temperature of pyrolyzing surface, K

T_∞ = ambient temperature, K

x = distance from the leading edge of the sample, m

y = distance from the surface to the interior of the sample, m

y_w = instantaneous location of the pyrolyzing surface, m

INTRODUCTION

In order to gain fundamental knowledge of fire phenomena, to extrapolate results beyond the experimental ranges, to interpret standard flammability tests, and to design fire-safe structures, mathematical methods are developed for pyrolysis and burning of materials. These models need certain properties of materials as input. One of the important properties is h_g , which is used in the equation for energy balance at the pyrolyzing surface as,

$$\dot{m}'' h_g = \dot{q}''_{NET} = \dot{q}''_{CONV} + \dot{q}''_{RAD FL} - \dot{q}''_{RERAD} + \dot{q}''_{EX} \quad (1)$$

where \dot{m}'' : mass loss rate or burning rate,

\dot{q}''_{NET} : net heat flux causing the solid fuel to gasify, pyrolyze, and eventually burn or be swept away with the surrounding gases,

\dot{q}''_{CONV} : convective heat feedback from gas phase to the pyrolyzing surface,

$\dot{q}''_{RAD FL}$: radiative heat feedback from flames absorbed by the pyrolyzing surface,

\dot{q}''_{RERAD} : radiative heat loss by the pyrolyzing surface to the surroundings,

\dot{q}''_{EX} : radiative heat feedback from surroundings other than the flame absorbed by the pyrolyzing surface

and the above heat fluxes are to be treated as magnitudes (all positive numbers).

The property h_g has been referred to by various names, such as the heat of pyrolysis (Sibulkin, et al. 1982), the heat of gasification (Sibulkin, 1986), the effective heat of vaporization (Fernandez-Pello, 1978), the heat of gasification/pyrolysis/depolymerization (Tewarson and Pion, 1976), the global

heat of gasification (Kashiwagi and Omori, 1988), and the effective heat of gasification (Magee and Reitz, 1974); we will continue to call it by this last name. It is a very important property in the calculation of burning rates (Sibulkin, et al. 1982), flame spread rates (Fernandez-Pello, 1978) and other characteristics of burning materials.

In the above equation, the value of the effective heat of gasification, h_g , includes heat conduction into the interior of a burning solid. When the solid burns in a steady state, thermally thick mode, the interior heat conduction is equal to the sensible enthalpy for heating the solid from room temperature to the pyrolyzing surface temperature, hence h_g is a constant; otherwise, it is not. Many mathematical models of burning solids have explicitly or implicitly assumed steady state burning with thermally thick material for which the use of a constant h_g is appropriate, however, the analytical results from these models are often compared with experiments and applied to practical situations in which there is transient heat conduction into the solid interior, which can introduce errors. That is, most models continue to treat the property h_g as the one which contains the effects of transient heat conduction into the burning surface. These effects, as shown later, can be significant and the value of the effective heat of gasification needs to be appropriately taken into account as a function of time. This paper attempts to examine the transient heat conduction and its effect on the estimation of h_g using measurements of solid interior temperature of burning, vertical PMMA slabs.

Several experimental studies have been conducted on burning of vertical slabs or cylinders of polymethylmethacrylate (PMMA) in fire and combustion research. PMMA is preferred in many wall fire studies primarily because it is an ashless burning solid, it does not yield very sooty flames, it is available in a form that does not drip very much, its surface temperature remains almost constant if

it is burning under zero or fixed external radiation heat flux, and many of its properties have been thoroughly investigated, including its effective heat of gasification, h_g . Values for h_g from 1512 to 1884 kJ/kg have been reported in the literature (Magee and Reitz, 1974 and Tewarson and Pion, 1976). All of the experimental and analytical studies known to the authors on burning of PMMA slabs or cylinders have used a constant value for h_g for further calculation of burning rates, energy analysis, spread rate, etc. Here, the question is, whether a PMMA slab burns like a thermally thick solid under the commonly studied experimental or analytical conditions. Most studies have used slabs or vertical solid cylinders of dimension 1.3 cm to 2.5 cm perpendicular to the burning surface; a few studies have used thicker slabs. In general, if a sample does not burn like a thermally thick solid and if the unsteady heat conduction to the interior is significant compared to the overall h_g , then one must use a transient value of h_g in heat and mass transfer calculations, or equivalently, take into account the transient heat conduction as a separate term.

The specific objective of the present experimental investigation is to measure conduction heat transfer into a vertical free and fully burning PMMA slab (having a nonpropagating fire), as a function of time and distance from the leading edge for clear and black PMMA and compare the change in its magnitude to the known values of h_g . A detailed analysis of these experiments is then presented in terms of the heat conducted away from the burning surface.

BACKGROUND

In a theoretical analysis of h_g for cellulosic materials, Sibulkin (1986) found that after an initial transient, the value of h_g for a semi-infinite slab remains nearly

constant at about twice the value of the heat of pyrolysis, h_p (a chemical property of material based on the difference of total enthalpy of volatile products of pyrolysis at the surface temperature and total enthalpy of solid at room temperature). For vaporizing fuels like PMMA, h_g was shown to decrease with time and in the steady, thermally thick limit it reached the value of h_p . Kashiwagi and Omori (1988) estimated the transient value of h_g for polymethylmethacrylate (PMMA) and polystyrene under flaming and nonflaming conditions for horizontal slabs under external radiation condition and found that h_g for high molecular weight PMMA decreases with time, for example, from over 5000 kJ/kg to about 2000 kJ/kg in about 6 minutes with an external radiant heat flux of 36 kW/m². Recently Jackson (1988) attempted to estimate the time-dependent heat of gasification for PMMA by exposing 9 cm diameter, 2.5 cm thick horizontal disks in an inert atmosphere. His estimation of heat of gasification at a near-steady state condition for high heat flux (40 kW/m²) was close to 1600 kJ/kg. He indeed discovered that the value of the heat of gasification is highly transient initially, for example, with an external heat flux of 10 kW/m², the heat of gasification decreased from as much as 55,000 kJ/kg at the beginning of gasification (which was at $t = 13$ min from the instant the radiation was turned on) to 5,500 kJ/kg in the first 1000 s, and it took almost 1000 s longer to reach the near-steady state value of 4,000 kJ/kg. At higher external radiation fluxes, the steady state was achieved earlier and the heat of gasification was considerably lower; the lowest value being 1600 kJ/kg. However, all these tests were carried out under non-burning, non-flaming conditions with a controlled flow of nitrogen gas over the sample.

Heat conduction in the solid interior of a burning PMMA slab or cylinder has been measured in other experimental studies, notably by Sibulkin and others (1974, 1975), Fernandez-Pello and Williams (1974), and more recently by

Ito and Kashiwagi (1988). However, in all of these studies, conduction heat loss to the interior was reported at the pyrolysis (or vaporization) front of a spreading flame, which is a fundamentally different configuration compared to the present experimental condition. Here, the emphasis is on finding out whether a fully burning slab or cylinder has a steady heat conduction loss to the interior, and if not, how much error will be introduced by assuming it to be a steady burning slab through the use of a fixed value of h_g . In a flame-spread situation, the interior heat conduction loss at the pyrolysis front may or may not be constant depending on the history of heating of the unburned fuel before the pyrolysis front reaches there, and therefore its unsteadiness and magnitude will strongly depend on the type of flame spread. This point is discussed later in view of the present experimental results. The importance of the present investigation lies in the fact that several analytical and experimental studies on burning PMMA have used a constant value of h_g in their analysis and data reduction (for example, Quintiere et al. 1986), and the question is whether it was a reasonable assumption.

EXPERIMENTS

A schematic of the apparatus and measurement scheme is shown in Figure D1. Samples of clear and black PMMA were cut 1.9 cm thick, 7.5 cm wide, and 15 cm high from a single large sheet for each type of PMMA. Black PMMA samples were tested mainly to investigate the effects of indepth radiation absorption, because other than absorptivity of the incident radiation, properties of black and clean PMMA differ very little. Samples were ignited with a flat flame burner using an identical, predetermined ignition procedure for all the test runs. The ignition procedure involved heating the sample sequentially at three different

vertical locations for ten seconds each, repeated four times. The front surface of the samples was fully involved before $t = 300$ s and was allowed to burn with natural air convection throughout the test. Samples were mounted on a vertical steel plate with side walls to prevent flames from wrapping around. Each sample was instrumented with fifteen, type K, 0.3 mm wire diameter thermocouples. They were embedded in the slab from behind in blind holes and glued using a PMMA solvent to ensure close thermal contact of thermocouples with the solid interior. The thermocouple junctions were at 2, 5, 8, 11, and 14 mm from the front (burning) surface at 3, 7.5, and 12 cm from the leading edge. The temperature was recorded at four-second intervals from all thermocouples for approximately 1000 s of total burning time using an automatic data acquisition system.

Once the temperature (T) vs. depth (y) distribution was measured, the heat conduction to the interior at the pyrolyzing surface, \dot{q}_c'' , was determined from the Fourier law as,

$$\dot{q}_c'' = -k \left. \frac{\partial T}{\partial y} \right|_{y=y_w}, \quad (2)$$

where k is the thermal conductivity of PMMA, for which a value of 2.688×10^{-4} kJ/m·s·K was used (Orloff et al. 1974). Since the pyrolyzing surface regressed as the sample continued to burn, the location of the pyrolyzing surface, $y = y_w$, had to be defined carefully. As mentioned earlier, it has been observed that the temperature of pyrolyzing surface of a free burning PMMA slab, T_w , remains approximately constant. We conducted separate experiments to measure T_w of clear and black PMMA using fine (50 μ m) thermocouples and they were found to lie in a very narrow temperature range as follows,

$T_w = 639.2 \pm 5$ K for clear PMMA,

$T_w = 638.5 \pm 5$ K for black PMMA.

The surface temperature of burning slabs may thus be assumed to be constant with good accuracy. The closeness of black and clear PMMA surface temperatures is expected because the surface temperature is mainly dictated by the pyrolysis chemistry of the solid for a given mode of burning. There is very little difference between the chemical composition of clear and black PMMA which contains a very small amount of carbon soot for color.

The measured temperature at various locations was curvefitted to the exponential function,

$$T(y) = A e^{-By}, \quad (3)$$

where A and B are constants. This curve was then extrapolated to $T = T_w$ to find the position of the pyrolyzing surface, $y = y_w$. The conduction heat loss then becomes,

$$\dot{q}_c'' = kAB e^{-By_w}. \quad (4)$$

In computing the heat flux at the pyrolyzing surface from the indepth solid temperature measurements, one has to be careful to avoid several possible errors. Beck (1962) discussed a similar situation and pointed out the “temperature disturbance” or the loading error caused by the difference in the thermal conductivities of the thermocouple material and material it is embedded in, and because of the thermocouple leads not being in an isothermal plane. However the error could not be estimated quantitatively by the parametric charts

given by Beck (1962) because the ranges of the charts are not suitable for the present conditions. Singh and Dybbs (1976) also discussed an error in temperature measurements caused by the contact resistance at the thermocouple junction and by conduction along the sensor leads. In the present experiments, although it is difficult to estimate the contact heat resistance quantitatively, our observations and approximate calculations show that the resistance is small, as follows. Each thermocouple wire was installed in place using a solvent CH_2Cl_2 with no insulation on the wires. When completely dried, the thermocouple wires were solidly and permanently embedded inside without contacting each other. Using the procedure of Singh and Dybbs (1976) and assuming that the contact resistance between the wires and the surrounding PMMA was very small, the estimated error between the sensed temperature and expected temperature in the absence of thermocouple was negligible. Therefore, the local temperature measurement is expected to reflect the actual interior temperature accurately.

The largest error in the estimation of temperature gradient at the surface is perhaps due to the extrapolation of the temperature data to the burning surface (defined as the location where $T = T_w$). If a higher-order scheme is used (such as a fourth-order polynomial or a fourth-order polynomial in the exponent of e), all five data points are connected; however, the behavior of the function beyond the data range can be very erratic and a root may not exist at $T = T_w$. An exponential functional form shown in Eq.3 was used because, in the absence of any significant indepth radiation, the temperature variation can be relatively closely simulated by the exponential function. The indepth radiation is mostly stopped at the bubbling, darkened surface before it reaches the first thermocouple; this is discussed later in detail.

It should be noted here that the emphasis of the present investigation is on pointing out the transient nature of the apparent value of the effective heat of gasification and, therefore, the relative magnitudes of the transient values of h_g are important. Conclusions based on these results will not be greatly affected by the possible errors discussed earlier.

RESULTS

Figure D2 shows a typical temperature distribution inside the solid as a function of the distance from the original front surface location at three different instants. As the time increases from 300 s to 700 s, the temperature continues to rise. After considering surface regression (which is approximately 8.0×10^{-3} mm/s after the sample is fully involved Kulkarni and Sibulkin, 1982), the rise at a given location will appear to be slower with respect to the pyrolyzing surface. When the data for clear and black PMMA are compared, it is apparent that the temperature of clear PMMA is greater at the first location, but the difference is very small deeper in the solid. This can be explained based on the indepth absorption of flame radiation incident at the surface. Recent measurements by Saito (1988a, 1988b) on 1.2 cm PMMA slabs show that the optical depth (based on the attenuation of incident radiation by a factor of $1 - e^{-1}$) is approximately 4 mm for clear PMMA and approximately 0.5 mm for black PMMA for a radiation source temperature of 1400 K. This means that for clear PMMA, a substantial amount of incident radiative energy can be absorbed in the first several millimeters of the surface. If there is a thermocouple junction embedded in the surface, the indepth radiation will be intercepted by the thermocouple junction and a corresponding temperature rise will be observed. However, it must be noted that the above-

mentioned optical depths were obtained for transient pyrolysis conditions without flaming; but in the present case the surface is pyrolyzing and flaming. A closer examination of the pyrolyzing surface of burning samples using floodlights showed that the surface is rough due to boiling action and it is blackened by the deposition of soot. In this situation, the indepth absorption of radiation at the surface for a clear PMMA sample will not be as large as for the non-pyrolyzing PMMA. Although an exact quantitative determination of indepth absorption is not possible here under flaming condition, this aspect is important and should be explored in the future. However, it may further be noted that none of the previous experimental studies on the measurement of interior heat conduction using thermocouples took this effect into account quantitatively. In the case of the black PMMA practically all the heat transfer at the first thermocouple at $y = 2$ mm is via conduction.

Figure D3 shows the temperature-time history at the thermocouple location nearest to the burning surface (2 mm in interior) for a clear PMMA sample. The temperature data taken at 4 s intervals were averaged over 40 s for clarity in plotting in this and the subsequent figures. The ignition procedure involved heating of the sample using a line burner at various locations in a particular sequence from $t = 0$ to 120 s and the samples appeared to be fully involved at around 300 s. This figure was plotted to check if the entire front surface of the sample was heated and ignited "simultaneously" (i.e., within a reasonably short interval of time). It is clear from Figure D3 that the temperature history at the three vertical locations (of 3 cm, 7.5 cm, and 12 cm from the bottom edge) is almost identical during a large part of the burn period (up to 800 s). This confirms that the interior temperature profiles had a negligible dependence on the height, and that the ignition procedure was satisfactory.

At $t > 800$, the thermocouple at 3 cm starts measuring higher temperature because the local mass burning rate is greater nearer to the leading edge, which roughly varies as $x^{-1/4}$ (Kim et al., 1971) for small-scale laminar fires such as those in the present experiments. Consequently, the thermocouple at the vertical location of 3 cm is partially uncovered while embedded in the bubbling pyrolyzing surface at around 800 s, and finally starts protruding out (based on visual observation) at around $t = 1000$ s.

Figures D4 and D5 show conductive heat flux to the interior derived from the temperature measurements for three test runs with clear PMMA and four test runs with black PMMA respectively, each at three different vertical locations (except where the thermocouples malfunctioned). Based on the accuracy of temperature measurement (± 2 °C), repeatability of time determination (± 10 s), location of the thermocouples in the interior, and most important, the scatter of the derived results for the heat flux, the accuracy of the heat flux results is estimated at around 10% at early times and up to 20% at later times.

The difference between heat fluxes at different heights is within the error of estimation of the heat flux and, therefore, the effect of vertical position is seen to be not significant in the present experiments. The surface conduction heat flux decreases with time and starts to reach a plateau at around 1000 s. There is a decrease from approximately 14 kW/m² for clear PMMA and 13 kW/m² for black PMMA at $t = 300$ s to almost 8 kW/m² at around $t = 1000$ s at which time the heat flux starts to approach a plateau. This indicates a substantial degree of unsteadiness in the early part of combustion of slabs. Similar unsteadiness was observed, but not quantitatively measured, by Sibulkin and Lee (1974) in the combustion of PMMA cylinders.

DISCUSSION

As mentioned in the Introduction, previous studies on the measurement of conductive heat loss into the interior of burning PMMA samples were aimed at estimating the heat flux at the pyrolysis front of a spreading fire in various orientations. In case of a downward-spreading fire, the unburned fuel is heated from room temperature to pyrolysis temperature in a relatively short distance and therefore the conductive heat flux into the surface is high. (The short-distance heating is caused by the closeness of the blue flame tip to the fuel surface.) On the other hand, for upward-spreading fires, the flames hang directly over the unburned fuel well before it reaches the pyrolysis temperature, therefore, the unburned fuel receives heat for a longer period before it reaches the pyrolysis temperature, and consequently, the conductive heat flux at the pyrolysis edge is relatively smaller. This phenomenon was clearly demonstrated recently by Ito and Kashiwagi (1988) who used holographic interferometry to probe the temperature field in the immediate interior of the surface. They showed that the interior conductive heat flux at the pyrolysis edge is as high as 70 kW/m^2 for downward spreading fires and 28 kW/m^2 for upward spreading fires. The interior conductive heat flux for downward flame spread at the pyrolyzing edge, derived from the thermocouple data of Sibulkin and Lee (1974) for PMMA cylinders and from those of Fernandez-Pello and Williams (1974) for flat sheets of PMMA, indicated values of 55 kW/m^2 and 73 kW/m^2 respectively.

In the present configuration, the fuel is systematically and slowly heated over a relatively large time period (well over 100 s). Consequently, the present results show a lower heat flux (around 14 kW/m^2) at ignition. The point to be made here is that the conduction heat flux to the interior is not constant in time and even at the ignition instant it can not be the same for various configurations.

It depends on the amount of preheating the sample undergoes prior to ignition. Since the present experiments were conducted with an identical ignition procedure for all test runs, the results may be further analyzed with self-consistency. As shown by the present data, a single value of conductive heat loss to the interior has no meaning because it is dependent on time as well as history prior to ignition.

If a slab burns like a thermally thick solid, the conduction heat loss to the interior will be given by

$$\dot{q}_c'' = \dot{m}'' c_p (T_w - T_\infty), \quad (5)$$

where \dot{m}'' is burning rate per unit area, c_p is the average heat capacity of the substance and T_w and T_∞ are temperatures at the pyrolyzing surface and ambient conditions, respectively. This equation assumes a constant c_p for PMMA, and a constant burning rate. Although the mass burning rate is a function of external heat flux on the burning surface (Saito et al, 1988), the present investigation is made for no external heat flux, and therefore, constant \dot{m}'' should be a reasonable assumption. Kulkarni and Sibulkin (1982) measured a local burning rate of approximately $9.5 \times 10^{-3} \text{ kg/m}^2\text{s}$ for PMMA slabs of similar size as those used here. Assuming $\dot{m}'' = 9.5 \times 10^{-3} \text{ kg/m}^2\text{s}$, $c_p = 2.1 \text{ kJ/kg}\cdot\text{K}$, $T_w = 366 \text{ }^\circ\text{C}$ and $T_\infty = 25 \text{ }^\circ\text{C}$, \dot{q}_c'' is found to be 6.8 kW/m^2 which is not very different from the value reached at the plateau in Figures D4 and D5. However, it must be noted that the slab thickness used in the present experiments was 1.9 cm with a 3 mm steel backing plate and therefore there was always some heat loss at the back surface of the samples.

There is a small difference between the computed conduction heat flux for clear and black PMMA as seen from the comparison of Figures D4 and D5. At

early times, the clear PMMA has a higher heat flux than the black PMMA, but later the trend is reversed. In any case, the difference is smaller than experimental errors and the scatter of the data, so no attempt is made to explain this phenomenon in terms of the small difference in temperatures and/or the difference in indepth radiation absorption characteristics of the two materials. As noted earlier, the indepth radiation is probably not very significant because the pyrolyzing surface is blackened by soot and it is uneven ("rough") because of bubbling at the surface.

Tewarson and Pion (1976) reported that for PMMA the heat loss at the surface was approximately 21 kW/m^2 . Their heat loss term was defined as the difference between the flame heat transfer to the surface and the heat flux required to pyrolyze the mass at the surface, in the absence of external radiation. Thus, it included the heat flux to the interior by conduction and the surface reradiation. Assuming $T_w = 366^\circ\text{C}$ and emissivity equal to 1.0, the radiation loss is approximately 9 kW/m^2 and therefore the present range of measurements of heat conduction to the interior are generally consistent with the measurements of Tewarson and Pion (1976).

Another point, and perhaps the most important outcome of the present investigation, may be noted as follows. Assuming a typical burning rate of $9.5 \times 10^{-3} \text{ kg/m}^2\text{s}$ and a value reported in the literature for h_g of 1600 kJ/kg , the net heat flux responsible for sustaining the burning rate is found to be, $\dot{m}'' \times h_g = 15.2 \text{ kW/m}^2$. The definition of h_g often assumes, and includes, a constant conductive heat loss into the interior, as discussed earlier and expressed in Eq. 1. Thus a 5 kW/m^2 change in the heat conduction loss to the interior will cause approximately 30% difference in the calculation of \dot{m}'' . Therefore, it is extremely important to take into account the instantaneous value of \dot{q}_c'' (heat conduction loss into the interior) in energy balance calculations where burning rate is derived from a

calculated or measured value of the net heat flux to the surface and a constant value for h_g .

Finally, a more global conclusion may be made from the results of the present study. Even though only vertical PMMA slabs were used in this investigation, one may reasonably argue that due to the unsteadiness in the solid interior heat conduction the effective heat of gasification should be cautiously used in case of burning of other materials and other orientations as well.

SUMMARY AND CONCLUSION

Conduction heat loss into the solid interior was determined for vertical, fully burning slabs of clear and black PMMA by measuring instantaneous temperature profiles inside the solid. Substantial unsteadiness was observed in the early part of combustion. Therefore, it is concluded that the thermally thick solid assumption is inappropriate in the early stage (first several hundred seconds) of the fire for combustion of PMMA slabs or cylinders of the typically used thickness of 1 or 2 cm. When the conduction heat loss into the interior reaches a plateau, the thermally thick slab assumption is reasonably in agreement with experimental results. Therefore, it is suggested that when estimating burning rates, the instantaneous value of the conduction heat loss into the interior should be used to avoid substantial errors. The conclusions from this study of vertical PMMA slabs may easily be extended to other materials and orientations.

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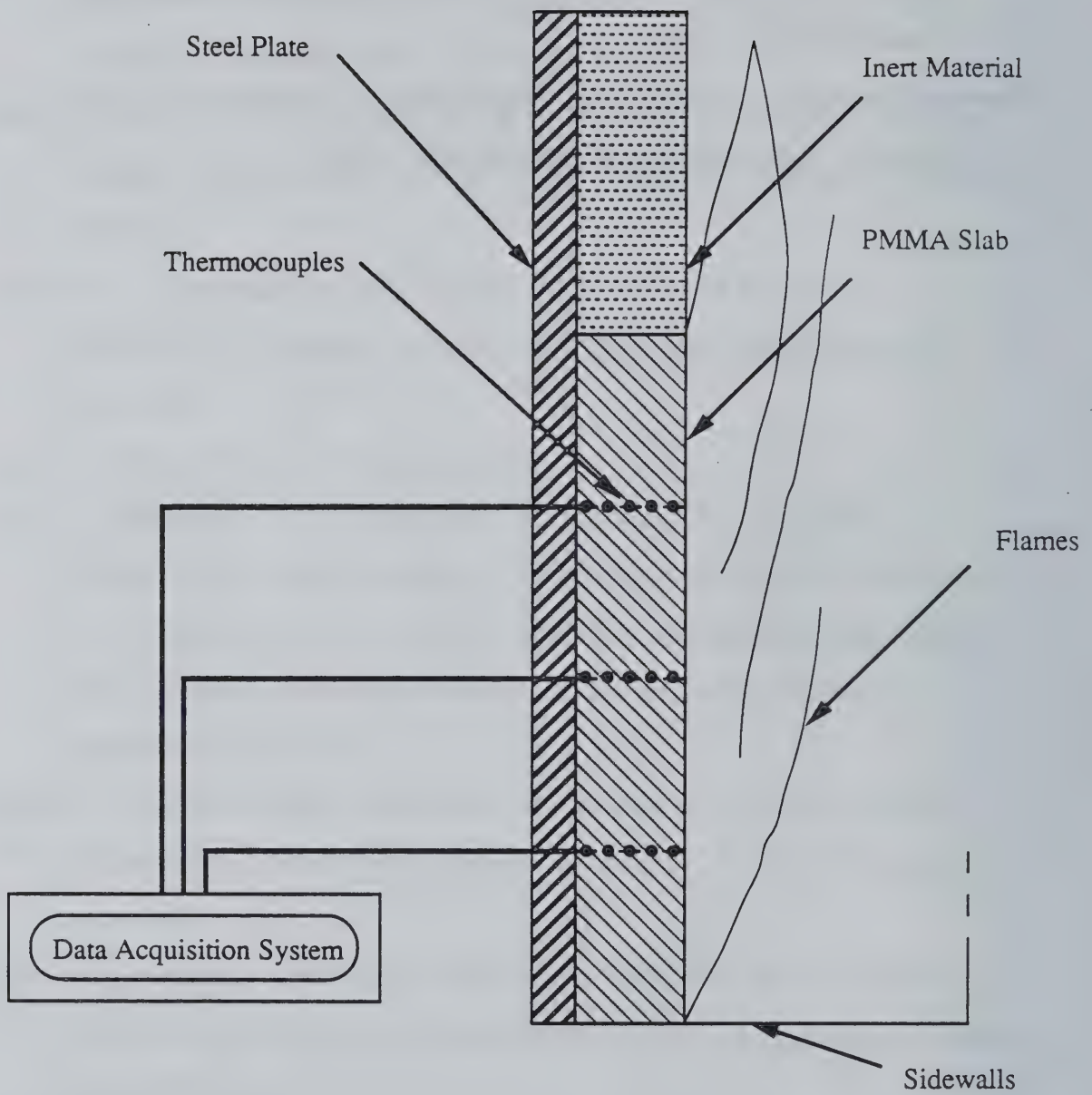


Figure D1. Schematic of Experimental Setup

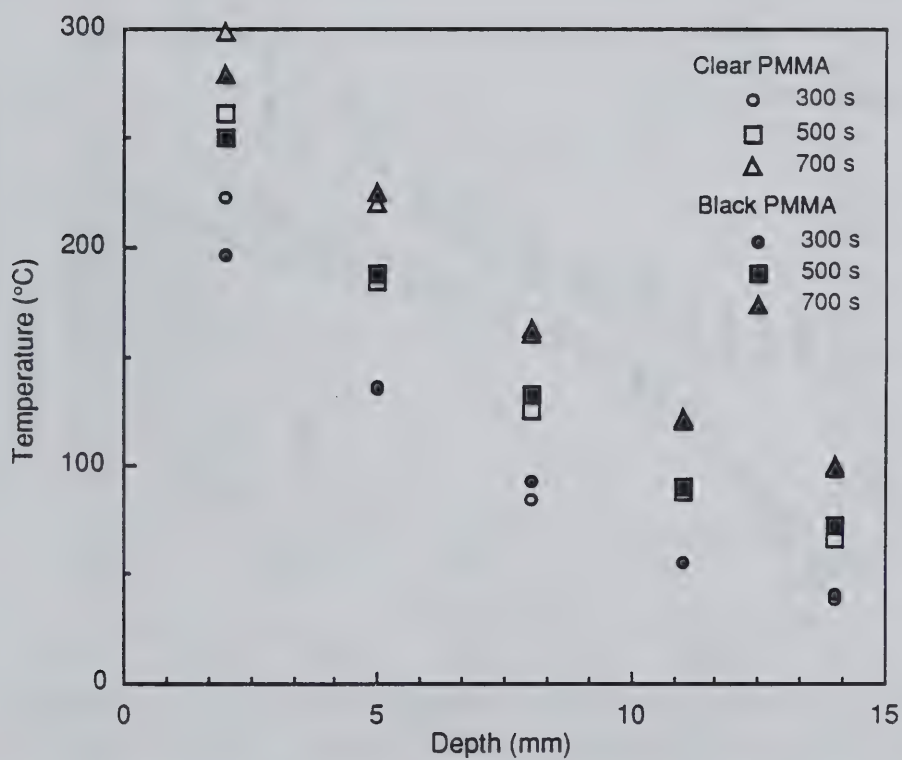


Figure D2. Measured Temperature Distribution in the Solid Interior of 1.9 cm Burning PMMA Slabs

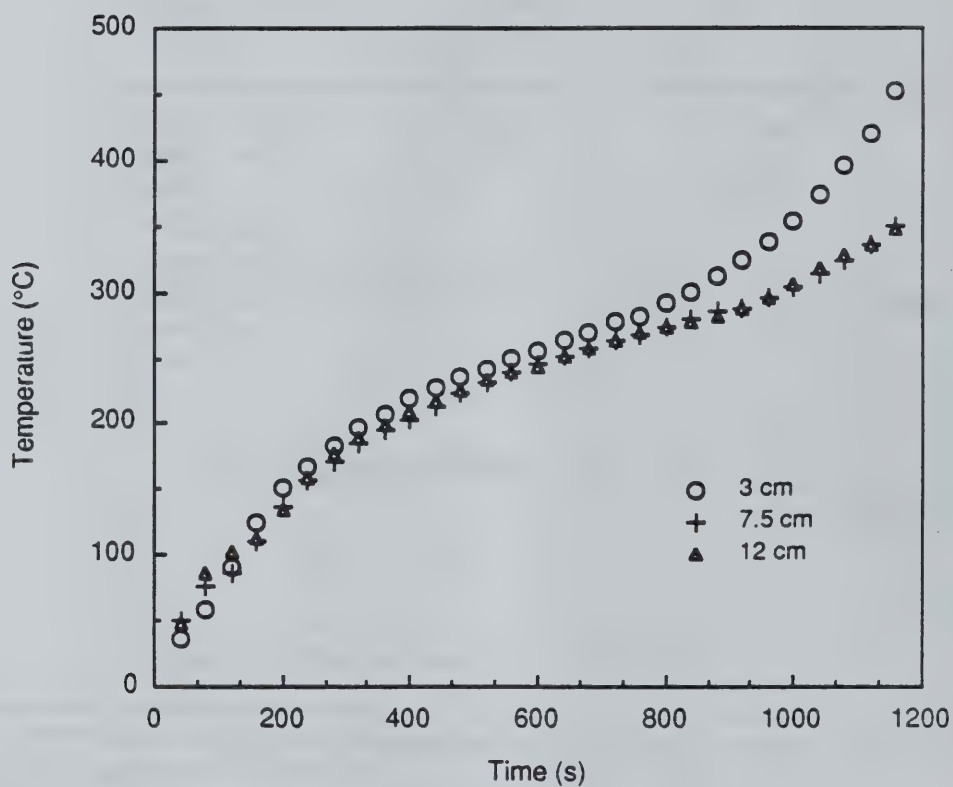


Figure D3. Temperature-Time History for Clear PMMA at a Depth of 2mm

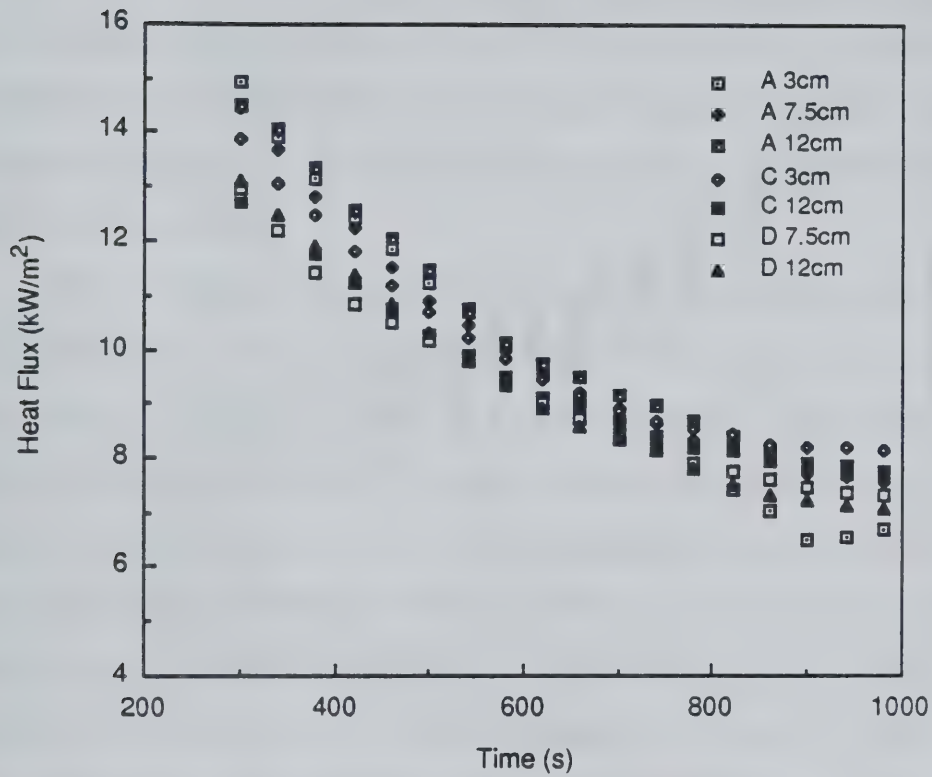


Figure D4. Conduction Heat Flux Derived from Temperature Measurements in Clear PMMA at Three Different Distances from the Leading Edge for Test Runs A, C, and D.

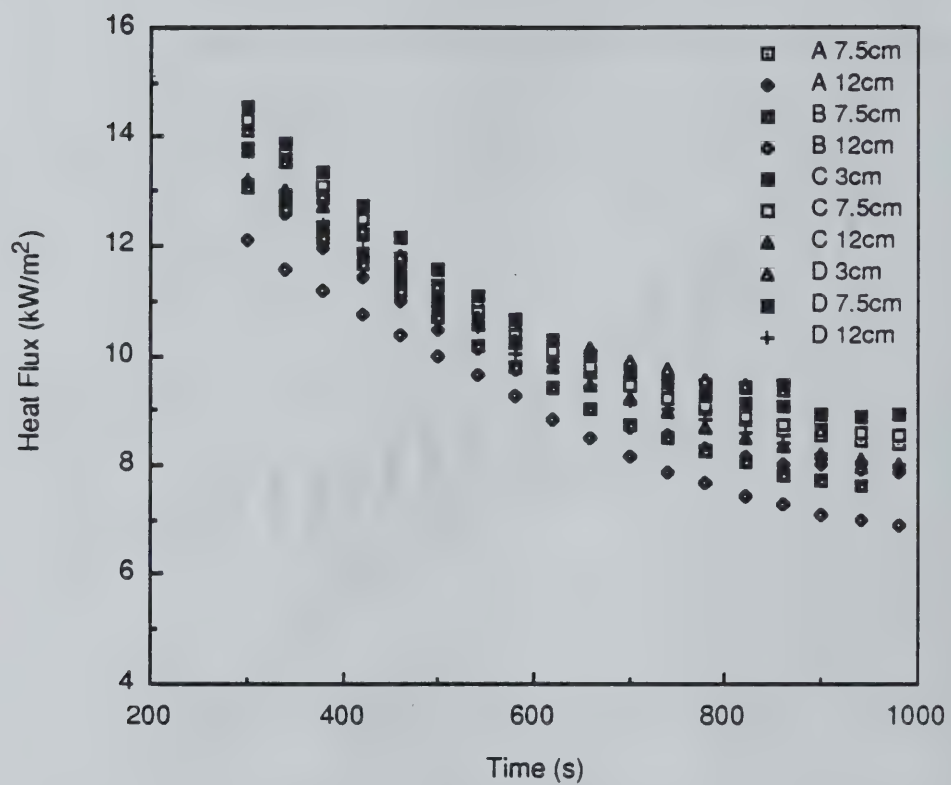


Figure D5. Conduction Heat Flux Derived from Temperature Measurements in Black PMMA at Three Different Distances from the Leading Edge for Test Runs A, B, C, and D.

Section E: CIRCULAR FOIL ("GARDON") HEAT FLUX GAGE CALIBRATION

The Gardon heat flux gages used in our upward spread apparatus need to be calibrated after every use; therefore, we have designed a device to allow comparative calibration. It involves selecting one of the gages (the "master gage"), which is never used in actual tests, and comparing it with other gages (to be calibrated) under identical heat flux conditions. A concurrent detailed study of the effects of (i) combined convective and radiative heat fluxes, and (ii) surface temperature discontinuity due to cooling on the measurement and estimation of heat flux is in progress.

The calibration device is illustrated in Figure E1. An enclosure consisting of a cylinder wall is designed with a gage plate which is exposed to a high density light source. The gage is mounted on the gage plate with a gage adaptor, which is used to hold the gage body in position. Heat source comes from a tungsten filament bulb of 250 watts. Under a certain electrical power, the radiative intensity from the bulb is approximately steady but somewhat nonuniform in the plane perpendicular to the light beam direction. Since the sensor's foil diameter is smaller than 5mm, a uniform incident radiation is a good approximation and the nonuniform effect of the radiation source may be neglected.

The basic steps in the operation of the device are: (1) turn on the power supply and hold it until the enclosure temperature reaches steady state, (2) mount the master gage and the recoated working gages in gage adaptors, (3) measure the master gage voltage, (4) turn the gage plate so that working gage is located exactly at the same spot where the master gage was positioned and then (5) measure the voltage of the working gage. The calibration factors are obtained by taking the average values obtained from each of the several different radiative intensities.

The calibration factors of four working gages are listed in Table 1, where the original calibration factor refers to that supplied by the manufacturer and the remaining factors were measured in the apparatus after using in three wall fire tests. (The working gages were cleaned and recoated before measuring the new calibration factors.) Clearly, the results show recalibrated factors are close to the original values. Also, it was found that some recalibrated gages had a higher absorptivity than the original value. The maximum deviation of new calibration factors compared to the manufacturer's calibration factors is within $\pm 4\%$.

Table 1. Calibration Factors $\left(\frac{W}{\text{cm}^2\text{-mV}}\right)$

	Original	I	II	III
Master Gage	0.662	—	—	—
Working gage #1	0.681	0.660	0.691	0.665
Working gage #2	0.649	0.660	0.678	0.649
Working gage #3	0.724	0.680	0.708	0.695
Working gage #4	0.688	0.690	0.710	0.672

The performance of master gage was checked over a long period by tracing its response to identical heat transfer environments at various times. The power supply can be controlled with a voltage fluctuation of less than 0.5 % and the measurement of the heat flux is made at a fixed time period after turning on the power supply. The data obtained from six tests, with at least 24 hours span between tests, are listed in Table 2 with a global deviation of voltage output below $\pm 3\%$ compared to the initial value. These results ensure that Gardon gage is robust and sound for reproducible measurements.

Table 2. Response of master gage (mV)

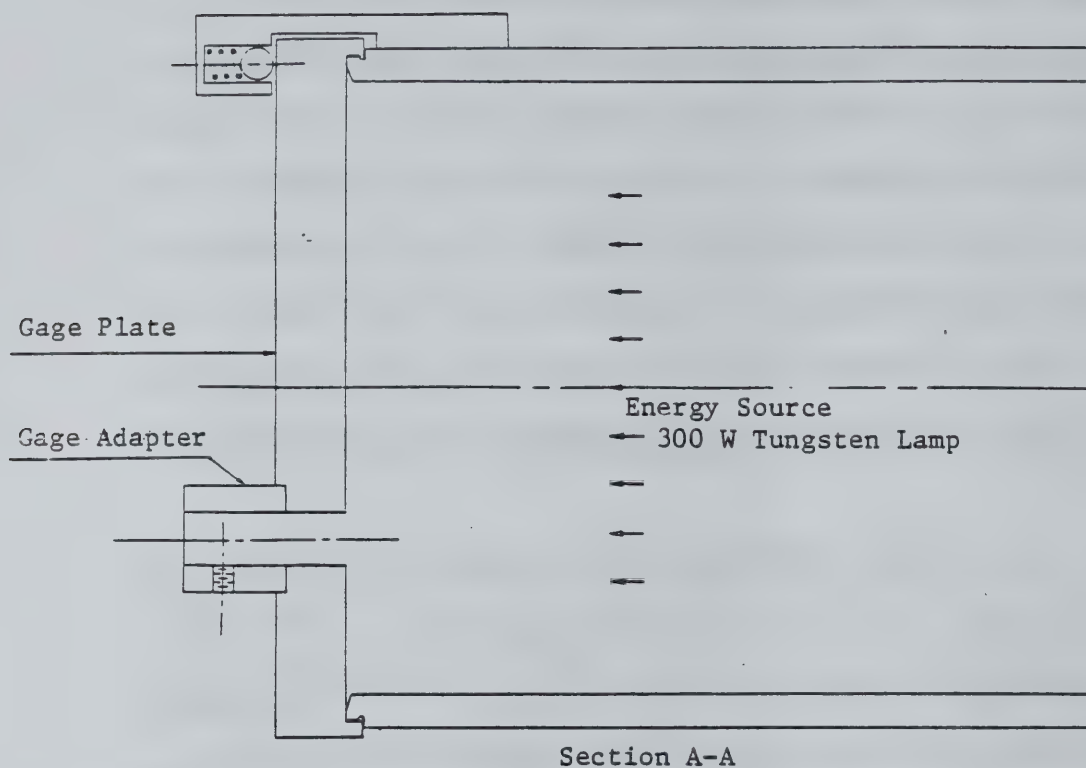
Test No.	80 V	100 V	120V
1	0.970	2.090	3.74
2	0.956	2.075	3.70
3	0.966	2.090	3.68
4	0.966	2.090	3.65
5	0.956	2.080	3.65
6	0.980	2.100	3.73

Another concern is about the surface condition during the experiment. The sensor's surface coating might be burnt out and then coated by soot. Therefore, after each experiment the working gages have to be calibrated to check whether the calibration factor had changed due to the soot covered surface. Results of two experiments are listed in Table 3 with a comparison of calibration factors before and after experiments. Clearly, the deviation is within $\pm 5\%$. This shows that we can ignore the soot-coating effect of the sensor during an experiment without introducing significant error into measurements.

Table 3. Comparison of calibration factors.

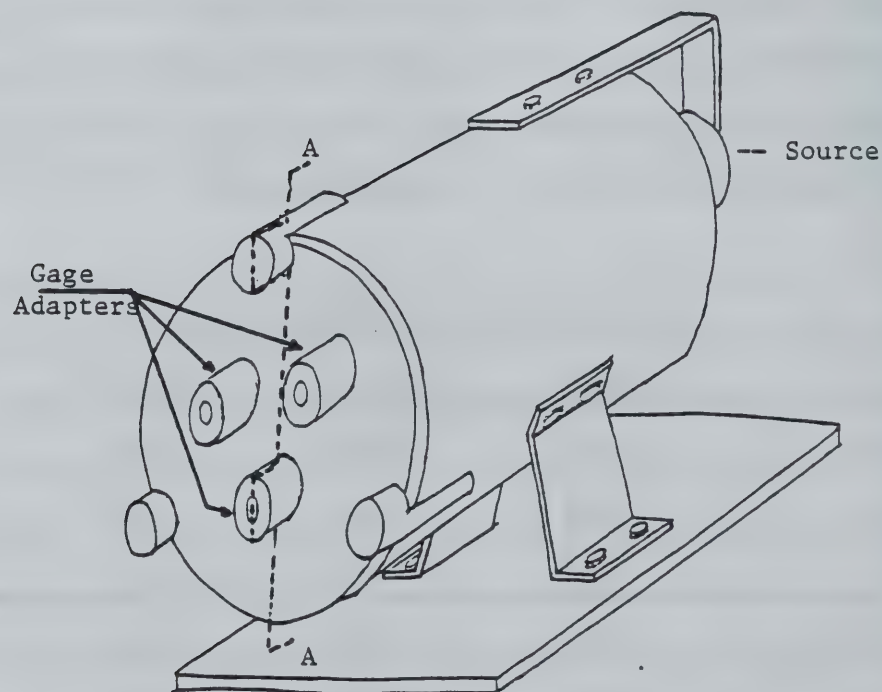
	Gage #1	Gage #2	Gage #3	Gage #4
Before Exp.	0.691	0.678	0.708	0.710
After Exp.	0.658	0.665	0.712	0.713
Error %	-4.8	-1.9	+0.6	+0.4
Before Exp.	0.660	0.660	0.680	0.690
After Exp.	0.680	0.662	0.700	0.690
Error %	+3.0	+0.3	+2.9	0

CALIBRATION DEVICE



MATERIALS :

1. Pipe S.S.
2. Adapter Cu.
3. Gauge plate Al.



FigureE1: Calibration device for 1/2" heat flux gages showing the internal arrangement and the external view.

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